Semi-Annual Report
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A. Task Objective: Algorithm Development for Global Mapping of Phycoerythrin Pigment, Dissolved Organic Matter, and Chlorophyllous Pigment

1. MODIS North Atlantic Test Site Establishment and Characterization

The Test Site includes the New York Bight/Mid-Atlantic Bight/Gulf Stream/Sargasso Sea and is conveniently located north and east of GSFC/WFF. As previously reported, the MODIS North Atlantic Test Site has been established as originally proposed. Much of the data obtained in the northwestern portion of the test site will be used for algorithm development in Case 2 waters. Characterization has been initiated by ship sampling, aircraft overflights, and analysis of historical data available from within the NASA AOL project since 1980.

a. During this semi-annual reporting period airborne missions were flown in the MODIS Test Site during late August and early September 1996 in conjunction with the the Russian Shirshov Institute of Oceanology. The flights were conducted near a ship cruise led by U. MD scientist Dr. Neil Blough. The cruise lines to the Gulf Stream were overflown on the northern portion and the southern portion. Backscatter instrumentation, a BBC-4, was supplied by Dr. Robert Maffione of SRI (now of Sequoia Instruments in Seattle, Washington). These airborne missions (and preliminary test flights) will allow further development of the phycoerythrin pigmentalgorithm. They will also provide additional evaluation of the recently-rebuilt AOL system and will provide data needed to further calibrate the fluorescence/Raman ratios derived from the AOL spectrometer data to retrieve CDOM and chlorophyll absorption coefficients.

As previously suggested, the above airborne flights allow continued evaluation of a new 256 channel ocean color spectroradiometer designed and built at Wallops Flight Facility. It was found that the color sensor possessed the requisite sensitivity for ocean color spectra in a high-rate/low-integration-time mode needed to allow editing of data containing sun glint. The prototype sensor was successfully flown during the JGOFS Iron Enrichment Experiments off the coast of Ecuador in November 1993. A still higher sensitivity detector and higher resolution sensor was successfully flown in March 1995 and during the JGOFS Arabian Sea Experiment. Evaluation of the data suggests that it is of good quality.

b. Other Data Acquisition for Algorithm Development

During October through December 1996 pervasive cloud cover allowed only two airborne flights in the MODIS Middle Atlantic Test Site: October 24 and 31. The October 31 data is superior to the October 24 data and will be further used to adavance the phycoerythrin algorithm development.

A manuscript describing some of the chromophoric dissolved organic matter (DOM) retrieval needed for the phycoerythrin algorithm work was published during a previous reporting period. The reader should consult this paper for details of the progress of the DOM retrieval using fluorescence methods. The paper is: Hoge, F.E., M.E. Williams, R.N. Swift, J.K. Yungel, and A. Vodacek, Satellite retrieval of the absorption coefficient of chromphoric dissolved organic matter in continental margins, Jour. Geophys. Res. 100, 24847-24854, (1995b).

This paper is complemented by a previous one that details the retrieval of CDOM absorption coefficient with airborne lasers: Inherent Optical Properties of the Ocean: Retrieval of the Absorption Coefficient of Chromophoric Dissolved Organic Matter from Airborne Laser Spectral Fluorescence Measurements by Frank E. Hoge, Anthony Vodacek, Robert N. Swift and James K. Yungel, Applied Optics 34, 7032-7038 (1995). The CDOM and the chlorophyll absorption must be satisfactorily modeled and retrieved before the weakly-absorbing phycoerythrin can be retrieved. A list of these and other recent publications is given near the end of this report.

New Algorithm Method. As reported in the last semi-annual report, a significant advance in the retrieval of inherent optical properties (whose list includes phycourobilin absorption coefficients and phycoerythrobilin absorption coefficients) was published during this semi-annual reporting period. The algorithm method is a major departure from the radiance ratios used in the old CZCS algorithms. The new method is based on radiance models derived from the radiative transfer equation (RTE). The linear matrix inversion technique is detailed in : Hoge, Frank E. and Paul E. Lyon, "Satellite Retrieval of Inherent Optical Properties by Linear Matrix Inversion of Oceanic Radiance Models: An Analysis of Model and Radiance Measurement Errors", Jour. Geophys. Res. 101, 16,631- 16,648, (1996). Work is now underway to extend the method to include phycourobilin and phycoerythrobilin absorption coefficients within the matrix inversion. No problems are anticipated with this effort.

a. The laser receiver modifications previously reported in the 2nd half of 1995 have been very successful. As we reported, in order to improve the laser measurement of phycoerythrin, the Airborne Oceanographic Lidar (AOL) was rebuilt during that reporting period to lessen the persistent stray light scatter problem in the spectrometer. The modifications include removal of the rigid light-guides and all turning mirrors comprising the original optical axis. A fiber optic face plate now occupies the focal plane of the new in-line optical path and transports the spectral radiation to mechanically reconfigured banks of original photomultiplier tubes. The resolution of each channel of the fiber optic face plate system is ~4nm but were optically combined at the photomultiplier tube face to achieve ~12nm per channel for this experiment. The signal path from the photomultiplier tubes through and including digitization remain essentially the same as reported previously. Compared to the original light guides, the fiber optic channels have superior scattered light rejection ascribed to a considerably smaller viewing or acceptance angle. Furthermore, a Bragg diffraction filter in the collimated segment of the light-path blocks passage of 532nm radiation to the diffraction grating and subsequent fiber optic focal plane. The 532nm pulse reflected from the Bragg diffraction filter is used to temporally define the ocean surface target and initiate digitization of the fluorescence spectra. A spectral and radiometric calibration is performed before and after each flight mission by viewing an internally illuminated 0.75m diameter calibration sphere placed beneath the aircraft telescope viewing port. Immediately following the 0.75m sphere calibration, a separate on-board 10cm calibration sphere is viewed by mechanically introducing (at the focal plane of the telescope) fiber-optically-delivered radiation from a tungsten lamp (followed by 40ns pulsed red LED's). The small calibration sphere allows immediate transfer of the 0.75m sphere calibration into the aircraft domain. The pulsed LED's then provide transfer of the ground (and onboard) DC tungsten lamp calibrations to the wide bandwidth pulsed portion of the AOL detection/amplification/digitization system. Calibration is maintained in flight by periodically viewing the 10cm calibration sphere. Complete details of the new AOL configuration are excepted to be described in other publications.

b. As previously reported, modifications to the AOL now have allow the discrimination of phycoerythrobilin and phycourobilin during airborne flights and the data are now being analysed for publication. Specifically, phycoerythrin fluorescence has been observed from airborne platforms since 1979. However, the spectral shifts associated with the individual phycobiliproteins (PBP), phycourobilin (PUB) and phycoerythrobilin (PEB), were not readily observable. Modifications to the original NASA Airborne Oceanographic Lidar (AOL) optics now permit spectral shifts associated with PEB and PUB pigments to be observed. This in turn allows possible application of the airborne methodology to wide area mapping of PEB and PUB spatial variability. This will significantly enhance the modelling and retrieval of these pigment absorptions due to phycoerythrin. A manuscript is now in preparation to report the observation of airborne laser induced spectral shifts associated with PUB and PEB pigments.

2. Selection of Case 1 Data Sets.

As given in a prior report, airborne active-passive ocean color data acquired within Case 1 oceanic regions with the NASA Airborne Oceanographic Lidar have now been screened for use in algorithm development. The AOL active-passive data in the northwestern Atlantic Ocean east of St. Johns , Newfoundland (obtained in 1989 as part of the Joint Global Ocean Flux Study of the North Atlantic Bloom Experiment) displayed remarkable quality and freedom from non-chlorophyllous backscatterers and is the basis of the forward modeling paper published in Applied Optics. The paper was reported above: Oceanic radiance model development and validation: Application of airborne active-passive ocean color data. This manuscript shows that voluminous, wide-area airborne active (laser) and passive (solar) ocean color spectral data can be used to develop radiance models and currently provide for their validation. The application of such models to algorithm development by direct inversion is under development. Such inversion was detailed in the recently developed ATBD. The St. Johns data, and that obtained in other regions of the ocean, is being used to establish the baseline radiance model to be used for the retrieval of phycoerythrin pigment (as well as DOM and pigment). Other data sets from the Monterey Bay flights (Sept 1992) and Mid- Atlantic Bight (April 1989 and 1991) are still under evaluation.

B. Other Work Accomplished

1. Additional Revision of the Algorithm Theoretical Basis Document (ATBD).

The ATBD revision is being rewritten and will be based on the radiative transfer equation (RTE). Additionally, the matrix inversion reported above will be applied to the new theoretical development. The new inversion theory shows promise for dramatically increased through-put of data. The revised document will detail the new procedure. Existing MODIS bands are expected to be sufficient to effect the linear matrix retrieval.

2. Ship Data.

During the next semiannual reporting period we expect to obtain data during overflight of the RV Cape Henlopen with Chief Scientist Dr. Neil Blough.

As previously reported in the above Limnology and Oceanography paper, recovery of the absorption coefficients for the light-absorbing or chromophoric components of the dissolved organic matter (aCDOM) from their fluorescence emission has been established by laboratory analyses of the surface samples gathered from the Feb. 28, 1991 cruise as well as other cruises. These absorbance and fluorescence analyses, (and work reported by others), show that absorption coefficients in the near ultraviolet can be directly retrieved from measurements of the fluorescence emission of CDOM. Thus, absorption coefficients in the visible spectrum can potentially be obtained from the fact that CDOM absorption is exponentially a function of wavelength. The errors in the laboratory fluorescence measurements were minimized through the combined use of the water Raman scatter as an internal radiometric standard and a quinine sulfate solution as a reference. This methodology reduces aCDOM algorithm retrieval errors (reported by other researchers) primarily attributable to the use of commercial spectrophotometers having maximum optical path lengths of 10 cm. While the aCDOM retrieval appears feasible, the relationship between aCDOM and CDOM fluorescence emission is susceptible to changes in CDOM fluorescence yield, so the continued temporal study of marine samples from many diverse oceanic locations is needed. When applied to shipboard and aircraft laser fluorometers, this retrieval methodology and the resulting CDOM absorption coefficients will be used in ocean color models and associated satellite sensor/algorithm development directly aimed at phycoerythrin retrieval.
The DOM is important since it is a major interferant to the detection and quantification of chlorophyll and chlorophyll accessory pigments (CAP) such as phycoerythrin. Moreover, DOM is a contributor to the carbon cycle itself.

3. Satellite Data Analysis

The retrieval of phycourobilin and phycoerythrobilin has been advanced by the recent demonstration of the retrieval of chromophoric dissolved organic matter from CZCS data. The results have been published in JGR as discussed above: Hoge, F.E., M.E. Williams, R.N. Swift, J.K. Yungel, and A. Vodacek, Satellite retrieval of the absorption coefficient of chromphoric dissolved organic matter in continental margins, Jour. Geophys. Res., in press, 1995. This is an important step toward the ultimate goal of retrieving CDOM, chlorophyll absorption coefficient, phycoerythrin absorption coefficient and total constituent backscatter.

A. In Situ Optical Characterization of the MODIS North Atlantic Test Site.

The continued characterization of the Test Site is partially described in the previously mentioned publications.

B. Phycoerythrin Algorithm Development Activities

Plans call for us to again directly address the quantification of the phycoerythrin signal as outlined in the original MODIS proposal. The phycoerythrin retrieval is being dealt with by inversion of ocean radiance models. Details of the phycoerythrin retrieval appear in the ATBD as submitted to the project office.

C. Chlorophyll Pigment and CDOM Corrections to the Phycoerythrin Algorithm.

As previously reported, major perturbations or influence to the ocean color spectrum are provided by chlorophyll, CDOM, and total constituent backscatter. These oceanic constituents significantly impede the retrieval of phycoerythrin pigment from the upwelled radiances. They must be dealt with in a systematic way in order to understand their effects and the impact on the retrieval of phycoerythrin and its ultimate quantification. In situ and airborne data gathered to date will be used to model the effects and to ascertain the extent that they can be quantified and removed. Recently published chlorophyll pigment models are being used for the pigment absorption. Our own CDOM model is being used for recovery of chromophoric dissolved organic matter. Finally, the literature is being surveyed for the best available detritus absorption model. The most pressing modeling problem is the availability of suitable chlorophyllous and nonchlorophyllous particulate backscatter models.

D. Anticipated Activities During Next Half Year.

1. Additional flights of the NASA Airborne Oceanographic Lidar are planned within the MODIS Test Site. Specifically, overflights of cruises of the research vessels in conjunction with the ONR/Univ. MD (Dr. Neil Blough)

2. No international field excursion is planned during 1996.

E. Recent Publications

1. Hoge, Frank E. and Robert N. Swift, Development and validation of satellite retrieval algorithms and derived

products: An emerging role for airborne active-passive (laser-solar) ocean color remote sensing, Paper 2964-06, SPIE Special Edition, Volume 2964, 92-99, (1996).

2. Hoge, Frank E. and Paul E. Lyon, "Satellite Retrieval of Inherent Optical Properties by Linear Matrix Inversion of Oceanic Radiance Models: An Analysis of Model and Radiance Measurement Errors", Jour. Geophys. Res. 101, 16,631-16,648, (1996).

3. Hoge, F.E., M.E. Williams, R.N. Swift, J.K. Yungel, and A. Vodacek, Satellite retrieval of the absorption coefficient of chromphoric dissolved organic matter in continental margins, Jour. Geophys. Res. 100, 24847-24854, (1995b).

4. Hoge, Frank E., Robert N. Swift, and James K. Yungel, Oceanic radiance model development and validation: Application of airborne active-passive ocean color spectral measurements, Applied Optics, 34, 3468-3476, (1995).

5. Hoge, Frank E., Anthony Vodacek, Robert N. Swift, James Y.Yungel, Neil V. Blough, Inherent optical properties of the ocean: Retrieval of the absorption coefficient of chromophoric dissolved organic matter from airborne laser spectral fluorescence measurements, Applied Optics, 34, 7032-7038, 1995.

F. Other Concerns

As reported previously, the lack of a 600nm band on MODIS-N is no longer felt to be the biggest problem facing the retrieval of the phycoerythrin pigment. Additional effort since the last report still suggest that radiance (and reflectance) models, can provide retrieval of the phycoerythrin pigment at the absorption peaks of 495nm (phycourobilin, PUB) and 545nm (phycoerythrobilin, PEB) can be achieved using the 490nm and 555nm MODIS bands. Of course, such retrievals will require a highly accurate model to account for the significant amounts of chlorophyll and DOM absorption occurring simultaneously with the phycoerythrin absorptions. The details of the phycoerythrin retrieval have been recently detailed in the ATBD but are being upgraded to linear matrix inversion of a radiance model that includes the phycoerythrobilin and phycourobilin absorption coefficients.